An ionized layer in a gas (in the atmosphere)

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The upper portion of the Earth's atmosphere, beginning at heights $z \sim 60$–80 km, is ionized. A plasma layer—the ionosphere—is formed, which encircles the Earth. The electron and ion densities in the ionosphere N increase up to heights $z \sim 300$ km, at which they attain values $N_m \sim 10^5$–10^6 cm^{-3}; above 300 km, N slowly decreases.

The ionosphere is capable of reflecting radio waves. This important property is widely used in radio communications at medium and short waves. The maximum frequency of radio wave reflecting from the ionosphere is $f_m \sim 20$–30 MHz; it is determined by the value of the electron density at the ionospheric layer maximum $f_m \sim \sqrt{N_m}$.[1] Radio waves with frequencies $f > f_m$ pass freely through the ionosphere without being reflected. It is, therefore, quite natural to raise a question concerning the possibility of stepping up the frequency f_m, i.e., increasing the maximum electron density in the ionosphere N_m by means of additional ionization of the latter.

In 1937, Bailey indicated a possibility of achieving additional ionization of the ionosphere by means of radio waves.[2] To accomplish this, he proposed to use gyro-resonance, i.e., resonance between the wave frequency and the natural gyro frequency of the ionospheric electrons in the geomagnetic field. The gyroresonance corresponds to the medium-wave band λ $\lambda \sim 200$ m, $f \sim 1.5$ MHz. The subsequent theoretical calculations[3,4] and experiments[5,6] have shown that this method calls for too great an expenditure of energy and that it cannot lead to a substantial increase in the reflecting power of the ionosphere. Similar results were also derived from calculations for the interaction between the lower ionosphere and radio waves with $f \sim 50$ MHz.[7] Any considerable increase in the maximum electron density in the ionosphere induced by radio waves appears not to be realizable as a result of the vigorous increase in the nonlinear absorption of the latter and a comparatively rapid diffusion of electrons away from the perturbed region.

Another approach centers around a theoretical investigation of a possibility to produce a plasma layer below the ionosphere, i.e., in the atmosphere at heights of 30–60 km.[8-10] It is proposed that the ionized region would result from an rf breakdown of air. This, and the subsequent maintenance of ionization are achieved by focused radio-wave beams. The ionization takes place in a region where the latter intersect. The breakdown is due to a short rf pulse, while ionization is sustained by either cw or pulsed radiation. In the case of maintenance by pulsed radiation, existence of a thin plasma layer in the crossed beams is possible. Such a layer is capable of effectively reflecting radio waves with a frequency $f \leq 1$–2 GHz, which exceeds the maximum frequency of radio waves reflecting from the natural ionosphere by nearly two order of magnitude.

Below, we shall consider the basic physical processes associated with the formation of an ionized layer in a gas.

1. Electrons, under the influence of a strong alternating rf field, accumulate considerable energy and acquire a capability to ionize neutral molecules of air with which they collide. Breakdown occurs when a sufficiently large number of ionization acts has taken place. The electron density N increases exponentially with time

$$N = N_0 e^{\nu_i t}, \tag{1}$$

where N_0 is the initial density and ν is the ionization frequency, i.e., number of ionizations produced on the average by a single electron per unit time. Attachment, recombination and diffusion which reduce the ionization growth may be neglected at sufficiently high values of ν_i.[11]

The ionization frequency ν_i is a function of the amplitude E_0 and the frequency ω of the alternating electric field and of the air molecule density N_m. It is shown in Fig. 1 as a function of $E_0/E_{\rm cr}$,[9] where $E_{\rm cr}$ is the critical field at which air breaks down:

$$E_{\rm cr} = 28\left(\frac{N_{\rm m}}{2{,}7\cdot 10^{19}\,{\rm cm}^{-3}}\right)\sqrt{1+\frac{\omega^2}{\nu_{\rm cr}^2}}\left(\frac{\rm kV}{\rm cm^3}\right),$$
$$\nu_{\rm cr} = 1{,}7\cdot 10^{-7}\,N_{\rm m}\,{\rm cm^3\,s^{-1}},\quad \nu_{\rm am} = 4\cdot 10^{-12} N_{\rm m}\,{\rm cm^3\,s^{-1}}; \tag{2}$$

here $\nu_{\rm cr}$ is the characteristic frequency of electron collisions and $\nu_{\rm am}$ is the maximum frequency of electron attachment. The field $E_{\rm cr}$ in Eq. (2) is expressed in kV/cm and N_m in cm^{-3} (at the pressure $p = 760$ mm Hg, $N_m = 2.7 \times 10^{19}$ cm^{-3}). When $E_0 = E_{\rm cr}$, ionization ν_i and attachment $\nu_{\rm am}$ frequencies become equal, and when $E_0 > E_{\rm cr}$, $\nu_i > \nu_{\rm am}$ and a breakdown occurs. Moreover, when $E_0 \lesssim 5E_{\rm cr}$, ionization is due only to relatively fast electrons with energies substantially exceeding the average energy of the plasma electrons. The number of such electrons sharply increases as the field intensifies. The ionization frequency increases correspondingly.

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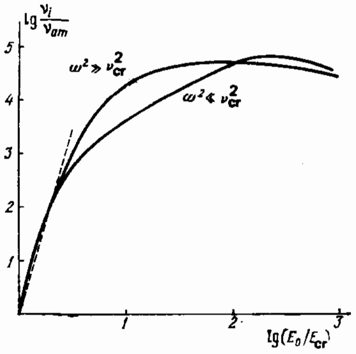


FIG. 1. Frequency of ionization in air ν_i as a function of the amplitude of an alternating electric field E_0. Dashed line indicates the empirical function of Eq. (3).

Thus, when E_0/E_{cr} varies from 1.3 to 3.0, the experimental data are defined by an empirical formula[13]

$$\frac{\nu_i}{\nu_{am}} \approx \left(\frac{E_0}{E_{cr}}\right)^{\alpha}, \quad \alpha \approx 5.3, \tag{3}$$

which is in good agreement with the theoretical curve (see Fig. 1). When $E_0/E_{cr} > 4$, the rate of growth of ν_i slows down, and at $E_0/E_{cr} \lesssim 10^2$ the ionization frequency attains a maximum and it slowly begins to decrease.[12] The latter is caused by a decrease in the total ionization cross section at high electron energies $\varepsilon > 10^2 - 10^3$ eV. The ionization frequency depends, mainly, on the ratio E_0/E_{cr}. Its dependence on ω and N_m for a fixed value of the latter is normally weak. The critical curves at $\omega^2 \gg \nu_{cr}^2$ and $\omega^2 \ll \nu_{cr}^2$ are shown in Fig. 1.

We shall determine the optimum conditions for ionization when for a given rf pulse energy the number of ions found in a gas is highest.[14] Under these conditions the bulk of rf pulse energy is expended in the production of electron-ion pairs. Taking into account the fact that the pulse energy density W is proportional to its duration Δt and the square of field intensity E_0^2, while Δt is inversely proportional to ionization frequency $\nu_i(E_0)$ for a given change in ion density, we find $W \sim E_0^2/\nu_i(E_0)$. The latter attains a minimum W_m (Fig. 2) when

$$E_0 = E_{0m} \approx (6-8) E_{cr}. \tag{4}$$

The first value of E_{0m} corresponds to a low-frequency limit ($\omega^2 \ll \nu_{cr}^2$), the second, to a high-frequency limit ($\omega^2 \gg \nu_{cr}^2$). The quantity $W_m \sim (\omega^2 + \nu_{cr}^2)/\nu_{cr}$ increases with ν_{cr} at both low ($\omega^2 < \nu_{cr}^2$) and high ($\omega^2 > \nu_{cr}^2$) frequencies. It is at a minimum when

$$\omega \approx \nu_{cr}. \tag{5}$$

Thus, Eqs. (4) and (5) define the frequency and the intensity of an alternating electric field for which the ionization of air is optimal.[1)]

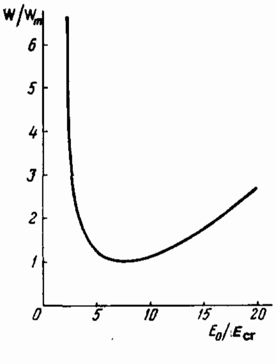


FIG. 2. Pulse energy W_2 required for ionization as a function of its amplitude E_0 at $\omega^0 \gg \nu_{cr}^2$.

TABLE I.

z, km	N_m, cm^{-3}	f, GHz	D, m	S, m^2	E_0, V/cm	P, GW	Δt_i, ns	Δt, ns	F, kHz	N, cm^{-3}	$\bar{P}$, kW	f_m, MHz
60	$6.7\cdot10^{15}$	0.3	100	10^6	25	25	500	12	0.1	$1.8\cdot10^8$	60	100
50	$2.2\cdot10^{16}$	1	100	$4\cdot10^4$	90	11	120	5	1	$1.7\cdot10^9$	100	300
40	$8.2\cdot10^{16}$	3	100	$6\cdot10^3$	350	12	30	1	10	$2\cdot10^{10}$	300	1000
35	$1.7\cdot10^{17}$	6	50	$2\cdot10^3$	700	50	15	0.5	30	$6\cdot10^{10}$	1500	2000

2. The ionization may be maintained by means of both periodically repeated breakdowns which are induced by short pulses and the continuous heating of a plasma. The former are preferred in the case of real atmospheric conditions.

The electrons acquire considerable energy from high-power pulses, and their velocity distribution function differs considerably from the equilibrium Maxwellian distribution. During a period between pulses, the electron distribution first undergoes a rapid relaxation to equilibrium, whereupon there occurs recombination which leads to disappearance of the electron-ion component of the plasma.

The relaxation of a perturbed electron distribution function to equilibrium after pulse cutoff is due to inelastic collisions between electrons and neutral molecules, which are accompanied by the excitation of optical, vibrational and rotational states of molecules, and also by ionization.[3,11] In a region of high electron energies $\varepsilon \gtrsim 15$ eV, the relaxation time is very short, $\tau \sim 10^7/N_m s$, where N_m is the density of molecules in air per cm^3 (see Table I). In a region of medium energies 1–2 eV $\lesssim \varepsilon \lesssim 15$ eV, τ is an order of magnitude higher, $\sim 10^8/N_m s$. At $\varepsilon \lesssim 1-2$ eV, electron-electron collisions are significant. In this case, the electron distribution function is Maxwellian and the electron temperature T_e is relaxed. At first, when $T_e \sim 1$ eV, the relaxation proceeds rapidly: $\tau \sim (10^8 - 10^9)/N_m s$; however, at lower temperatures, $T_e \sim 0.1$ eV, it is considerably slower. The total relaxation time from T_e to the neutral molecule temperature $T \sim 300\ K$ is $\tau \sim (1-3) \times 10^{11}/N_m s$.

The electrons disappear during intervals between pulses maintaining them as a result of direct recombination, or become attached to molecules with the subsequent recombination of positive and negative ions. The recombination proceeds basically after the completion of relaxation of the electron distribution function, i.e., in a steady-state plasma with an electron temperature similar to neutral molecule temperature T. The recombination processes in the atmosphere have been studied sufficiently.[15,16] Among direct processes, the leading role is played by dissociative recombination.

[1)] Equations (4) and (5) are valid for a sufficiently high plasma pressure when diffusion is unimportant.[11]

Electron attachment is mainly due to triple collisions, and detachment, to collisions with excited oxygen molecules O_2' and the associative processes which take place in collisions between oxygen O and nitrogen N atoms. The recombination of positive and negative ions occurs basically in the course of pair collisions which is accompanied by excitation of molecules. The processes of ion kinetics in the atmosphere are complex and diverse, and substantially depend on small admixtures of chemically active components. The reaction coefficients are known,[15,16] and may be used to calculate variations in the ionization balance. Figure 3 shows the electron N and negative ion N^- densities for the case of a periodically-pulsed maintenance of ionization. The dashed lines indicate the approximate average steady-state values of the two densities.

It should be noted that the conditions in a plasma during multiple pulsed breakdowns may be quite different from those which existed at the time of the initial breakdown. First, a considerable ionization persists up to the onset of the next breakdown. Second, changes may occur in the state of the basic components of air which are associated with the excitation of slowly-attenuating metastable and vibrational levels of a molecule. The presence of vibrational states affects both the kinetics of overall heating of a gas[17] and the conditions for the occurrence of a repeated breakdown.[18] Variations in the chemical composition of air also occur, and the presence of small admixtures ($\sim 10^{-3}\%$) of a number of gases (H_2O, NO, N, O, O_3, O_2', etc.) in air noticeably affects the recombination kinetics.[15]

The neutral components of air in a discharge are heated basically as a result of thermalization of the excited vibrational levels of molecular nitrogen (so-called V-T relaxation).[17,19] In the pulsed ionization maintenance mode the heating of the neutrals is not great: $\Delta T/T \leqslant 0.1$. Continuous maintenance of ionization may be used to produce strong heating of a gas, to 3000 K. At these temperatures, considerable isothermal ionization of air takes place $N/N_m \sim 10^{-5}-10^{-7}$. However, support of the isothermal ionization under actual atmospheric conditions calls for major energy expenditures which are attributed to atmospheric winds.[8] The effect of the latter is much less pronounced in the case of pulsed maintenance of ionization.[10]

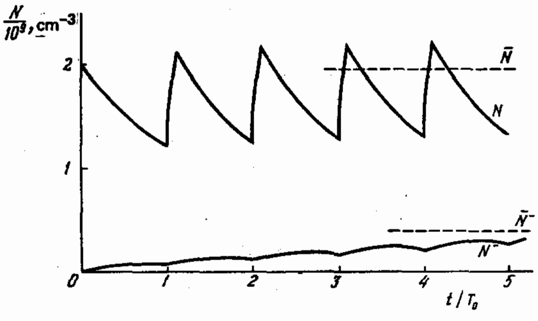


FIG. 3. Electron N and ion N^- densities as functions of time t in the case of periodic maintenance of ionization. Ionization per pulse $\Delta N = 10^9$ cm^{-3}; time between pulses $T_0 = 10^{-3}$ s. Initial ionization $N_0 = 2\times10^9$ cm^{-3}, $N_0^- = 0$.

3. In order that the location of an ionized region in the atmosphere may be fixed, the region must be produced where two or more rf beams intersect. The ionized region, moreover, assumes a specific structure.

The ionized region formed by the intersection of two identical rf beams constitutes a set of planes which are parallel to the bisecting line of the angle between the intersecting beams and the direction of the electric polarization vector of the radio waves (Fig. 4). The distance between the planes is given by

$$a = \frac{\lambda}{\sin(\varphi/2)}, \qquad (6)$$

where $\lambda = c/f$ is the wavelength of the ionizing radio waves, and φ is the angle between the crossed beams. The thickness of the ionized layer in the case of weak diffusion is given by

$$d \sim (0.1-0.2)\,\lambda. \qquad (7)$$

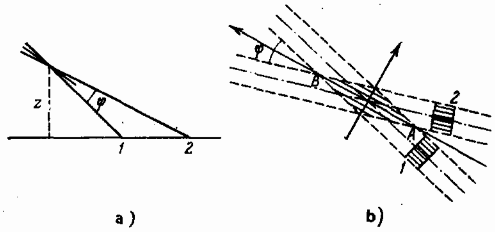
The maximum ionization occurs in the main layer which passes through the point where the beam intensity maxima intersect. In the case of ionization maintenance by short pulses, appropriate pulse duration, repetition frequency and intensity are selected to sustain only the main layer or several adjacent layers. A single broad ionized layer is formed as a result of extensive diffusion, which overlaps several ionization planes. The general condition for the maintenance of an ionized layer is

$$\bar{\nu}_i > \nu_a + \frac{v_n^2}{4D_a} + \frac{D_a}{4d^2}; \qquad (8)$$

where $\bar{\nu}_i = \nu_i \Delta t/T_0$ is the mean ionization frequency (Δt is maintenance pulse duration, T_0 is the time between pulses), ν_a is the frequency of attachment, v_n is the wind velocity in the direction of the normal to the layer, D_a is the coefficient of ambipolar diffusion, and d is the layer thickness.

The plasma stability analysis shows that a quasi-steady-state nonuniform structure may develop in the plasma due to the ionization instability.[20] The characteristic size of the resultant inhomogeneities is of the order of λ. These become stronger as the maximum electron density increases.

4. Let an ionized layer be formed at a height z in air in a region where two beams intersect. The molecule density $N_m(z)$ is fixed by this, and the frequency ω and field intensity E_0 of radio waves are, under the optimum conditions, uniquely related to N_m by Eqs. (2), (4)



a) b)

FIG. 4. Breakdown and the ionization maintenance by means of crossed radio pulses 1 and 2. (a) general scheme; (b) intersection region geometry, AB—main ionization layer.

and (5). The duration of maintenance rf pulses is determined by the ionization frequency $\Delta t \sim 1/\nu_i$, and the repetition frequency F by the recombination rate. Table I shows the characteristic parameters which are required to establish an ionized layer in two crossed beams at various heights z in air. Here f is the frequency of radio waves which produce an ionized layer, D is the antenna diameter, S is the area of the ionized layer, E_0 is the field intensity, P is the power of each beam, Δt_1 and Δt are the duration of breakdown and maintenance pulses, respectively, F is the maintenance pulse repetition frequency, N is the mean electron density at the layer maximum, $\bar{P}$ is the average power expended to maintain an ionized layer, and f_m is the maximum frequency of radio wave which are effectively reflected from the ionized layer.

The heights at which an ionized layer is produced are limited to 30–60 km since appreciable absorption of strong radio waves occurs above that ceiling (60 km) due to the presence of the ionosphere which the radio waves must pass before reaching the ionization region.[3,4] At heights lower than 35–40 km the power required to maintain ionization increases rapidly. Moreover, the optimum conditions at heights $z \leqslant 30$ km correspond to radio waves with frequencies $f > 10$ GHz (or $\lambda < 3$ cm), which may experience considerable absorption in the lower layers of the atmosphere as a result of inclement weather conditions.[21]

The estimates shown in Table I indicate that the formation of an ionized layer in the atmosphere, which is capable of reflecting radio waves with frequencies up to 1–2 GHz, is achievable. Such a layer may be used for relaying television, radio and telephone signals, and for other means of radio communications in a broad frequency band from 20 MHz to 1–2 GHz.

[1] V. L. Ginzburg, Rasprostranenie elektromagni tnykh voln v plazme (Propagation of Electromagnetic Waves in a Plasma), Nauka, M., 1967.

[2] V. A. Bailey, Nature **139**, 68 and 838 (1937).

[3] V. L. Ginzburg and A. V. Gurevich, Usp. Fiz. Nauk **70**, 201 (1960) [Sov. Phys. Usp. **3**, 115 (1960)]; Nelineĭnaya teoriya rasprostraneniya radiovoln v ionosfere (Nonlinear Theory of Propagation of Radio Waves in the Ionosphere), Nauka, M., 1973.

[4] É. I. Ginzburg, Geomag. aeronom. **7**, 104 (1967).

[5] V. A. Bailey, R. A. Smith, K. Landecker, A. J. Higgs, and F. H. Hibberd, Nature **169**, 911 (1952).

[6] I. S. Shlyuger, Pis'ma Zh. Eksp. Teor. Fiz. **19**, 274 (1974) [JETP Lett. **19**, 162 (1974)]; A. V. Gurevich and I. S. Shlyuger, Izv. Vyssh. Uchebn. Zaved. Radiofiz **18**, 1237 (1975); A. V. Gurevich, G. M. Milikh, and I. S. Shlyuger, Pis'ma Zh. Eksp. Teor. Fiz. **23**, 395 (1976) [JETP Lett. **23**, 356 (1976)]; Izv. Vyssh. Uchebn. Zaved. Radiofiz. 20, 1790 (1977).

[7] P. P. Lombardini, Radio Sci. Ser. D **69**, 83 (1965).

[8] A. V. Gurevich, Geomag. aeronom. **12**, 631 (1972).

[9] A. V. Gurevich, *ibid.* **19**, 633 (1979).

[10] N. D. Borisov and A. V. Gurevich, *ibid.* **20**, 841 (1980).

[11] A. D. MacDonald, Microwave Breakdown in Gases, Krieger (1966) [Russ. Transl. Mir, M., 1969].

[12] S. G. Arutyunyan and A. A. Rukhadze, Krat. Soobshch. Fiz. (FIAN SSSR), No. 9, 12 (1978).

[13] G. C. Light and E. C. Taylor, J. Appl. Phys. **39**, 1591 (1968).

[14] A. V. Gurevich, D. M. Karfidov, N. A. Lukina, and K. F. Sergeĭchev, Geomag. aeronom. **20**, 953 (1980).

[15] M. J. McEwan and L. F. Phillips, The Chemistry of the Atmosphere, Halstead Pr. (1975) [Russ. Transl. Mir, M., 1978].

[16] C. A. Blanck, M. H. Borther, T. Bauer, and A. A. Feryck, A. Pocker Manual of the Physical and Chemical Characteristics of the Earth's Atmosphere, DNA 346711, Washington, 1974.

[17] S. A. Zhadaonv, L. P. Napartovich, and A. N. Starostin, Zh. Eksp. Teor. Fiz. **76**, 130 (1979) [Sov. Phys. JETP **49**, 66 (1979)].

[18] N. D. Borisov and G. M. Milikh, Fiz. Plazmy **6**, 917 (1980) [Sov. J. Plasma Phys. **6**, (*sic*) (1980)].

[19] B. F. Gordiets and Sh. S. Mamedov, Prik. Mekh. Tekh. Fiz. **15**, 13 (1974); B. F. Gordiets, A. I. Osipov, E. V. Stupochenko, and L. A. Shelepin, Usp. Fiz. Nauk **108**, 655 (1972) [Sov. Phys. Usp. 15, 759 (1973)].

[20] V. B. Gil'denburg and A. V. Kim, Zh. Eksp. Teor. Fiz. **74**, 141 (1978) [Sov. Phys. JETP **47**, 72 (1978)]; V. B. Gil'denburg and S. V. Golubov, Zh. Eksp. Teor. Fiz. **67**, 89 (1974) [Sov. Phys. JETP **40**, 46 (1975)]; V. B. Gil'denburg, V. P. Golitsyn, and V. G. Semenov, Izv. Vyssh. Uchebn. Zaved. Radiofiz. **17**, 1718 (1974).

[21] Ya. L. Al'pert, V. L. Ginzburg, and E. L. Feĭnberg, Rasprostranenie radivoln (Propagation of Radio Waves), Gostekhizdat., M., 1948.

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